Appendix D

Fluid-selection tool

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(NLR, The Netherlands)

Abstract

Fluid selection is one of the first and most important steps for the design of a thermal control system. The usual approach to fluid selection is to manually evaluate many different fluids. However, this is a very time-consuming process, since the number of fluids to choose from is very large, and the best fluid strongly depends on the application and temperature range. Furthermore, a potentially suitable fluid can be overlooked when fluids are manually selected. For these reasons, NLR developed a systematic, automated, fluid-selection tool. This fluid selection tool is implemented in Matlab, and it uses a figure of Merit to select the most suitable fluids from the REFPROP database. In this presentation, the use of the fluid selection tool is demonstrated for 4 different applications: Heat Pipe, Loop Heat Pipe, Two-phase mechanically pumped loop, and a heat pump. For example, it is explained why CO_2 is used in the thermal control system of AMS02 (which was launched with the space shuttle in May 2011 and subsequently mounted on the International Space Station) and why isopentane is selected for an ESA Heat Pump application.
With the fluid selection tool, fluids can be selected which would have been overlooked without the use of the figure of Merit. Furthermore, the tool offers a large saving in ccosts and time since the tedious process of finding and analyzing possibly suitable fluids can now be carried out with a single push on a button.

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Fluid selection tool

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Nationaal Lucht- en Ruimtevaartlaboratorium – National Aerospace Laboratory NLR

Introduction

- Fluid selection is one of the first and most important steps for the design of a thermal control system
- The number of fluids to choose from is very large, and the best fluid strongly depends on application and temperature range
- Usually, the approach to fluid selection is to manually evaluate many different fluids

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Introduction

- This is a very time-consuming process
- Furthermore, very often the wrong fluids are analyzed and 'good' fluids are missed:
  - Standard fluids often have a poor performance in space applications, because the temperature range is usually very different than for terrestrial applications
  - Fluid flammability and/or toxicity are less an issue for space applications than for terrestrial applications
- Because of these reasons, NLR developed a systematic, automated, fluid-selection tool

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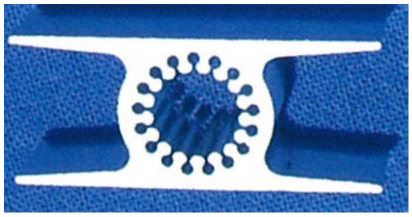
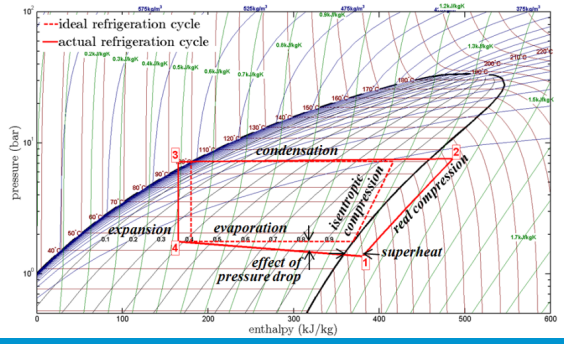
Introduction

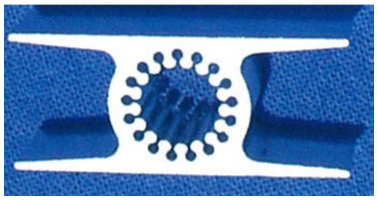
- The fluid selection uses the 'figure of Merit'
- In this presentation, the use of the figure of Merit is demonstrated for 4 different applications
  - Heat pipe
  - Loop Heat Pipe/Capillary Pumped Loop
  - Two-phase mechanically pumped loop
  - Heat pump

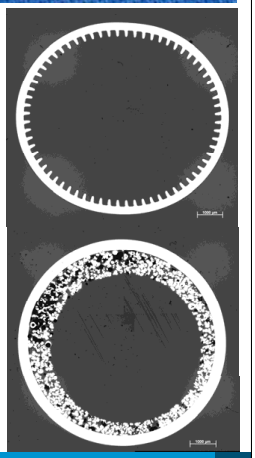


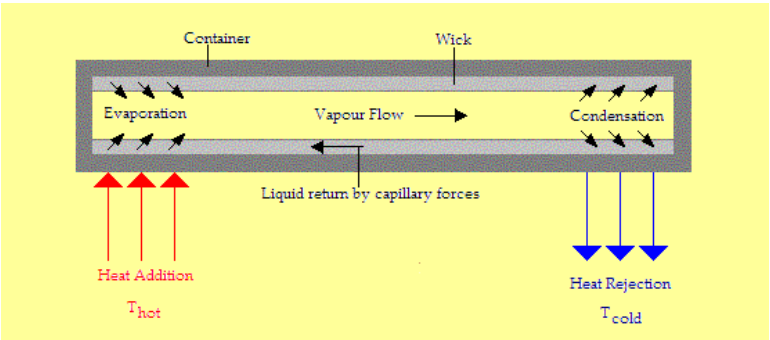


Heat Pipes

- Heat Pipes are capillary driven two-phase heat transfer devices
- Can transport large amounts of thermal energy with only a small ΔT (~10000 better than copper)
- Usually water or ammonia as working fluid







Heat pipes

- There are several limits to the heat transport capacity of a heat pipe (capillary limit, entrainment limit, sonic limit etc.)
- The capillary limit is usually the most restrictive: $\Delta p_{\mathrm{cap,\,max}} > \Delta p_{\mathrm{friction}}$
- From this capillary limit, the maximum heat transport capacity *P* is derived:

geometry dependent *fluid dependent*

$$P \propto \frac{d^3 N}{L} \frac{\rho_l h_{lv} \sigma}{\mu_l}$$ figure of Merit for heat pipes (well known from literature)

- The fluid selection tool plots the figure of Merit for all the fluids in the REFPROP fluid database

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Heat pipes

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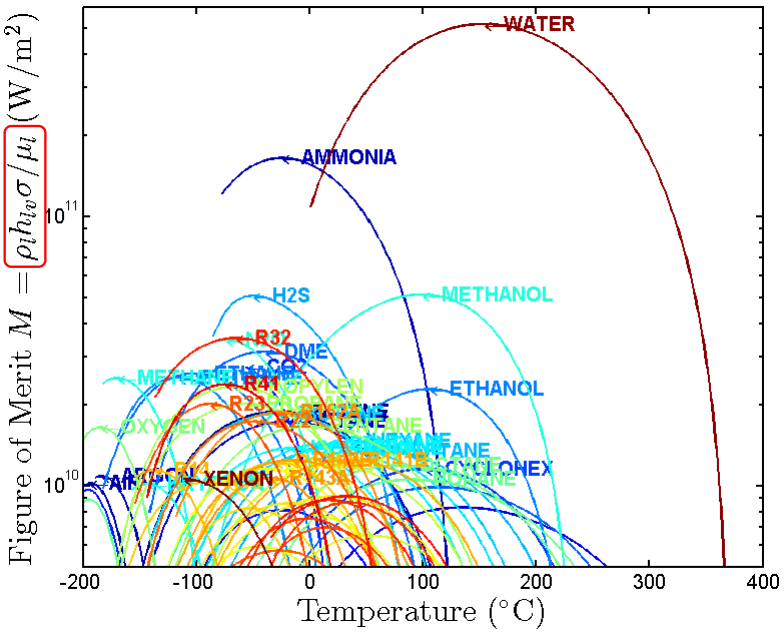

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Loop Heat Pipe

- For a Loop Heat Pipe, the figure of Merit is similar to that of a Heat Pipe
- The major difference with a Heat Pipe is that the vapour pressure drop is usually dominant over the liquid pressure drop
- The flow in the vapour line is generally turbulent
- The figure of Merit for LHP then becomes:

$$M = \frac{\rho_v {h_{lv}}^{7/4} \sigma}{{\mu_v}^{1/4}}$$ figure of Merit for Loop Heat Pipes [1]

[1] N. Dunbar, P. Cadell, *Working fluids and Figures of Merit for CPL/LHP applications*, CPL-98 Workshop (1998)

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Loop Heat Pipe

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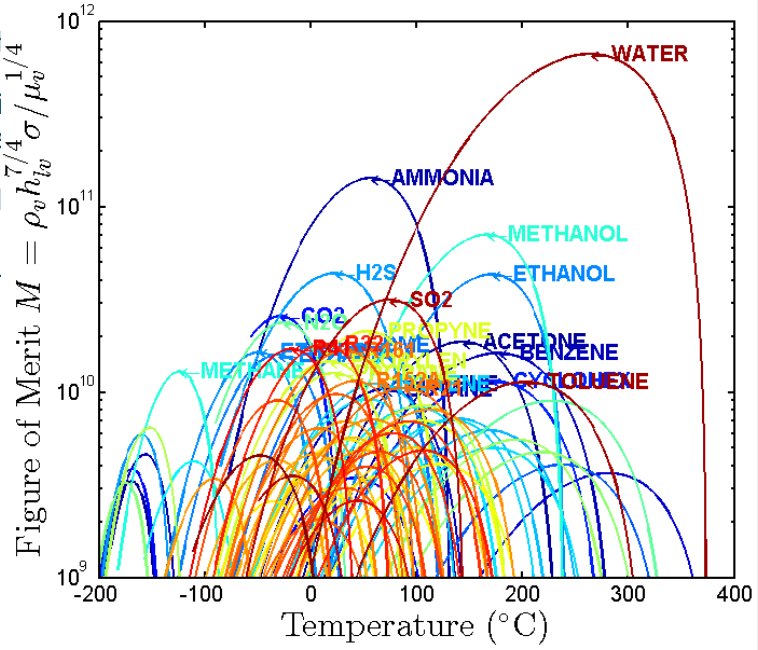

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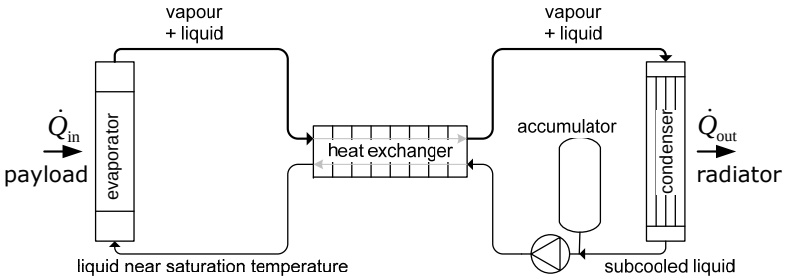
Two-phase Mechanically Pumped Fluid Loop

- In a 2Φ-MPFL, thermal energy is transported by circulating a fluid which evaporates and condenses at almost constant temperature
- Advantages compared to single-phase (e.g. water, glycol) cooling:
  - very uniform temperature
  - low mass flow (typically 10 to 100 times lower)
  - much smaller tubing diameter
  - much higher heat transfer coefficient



Schematic drawing of a 2Φ-MPFL (click drawing for video)

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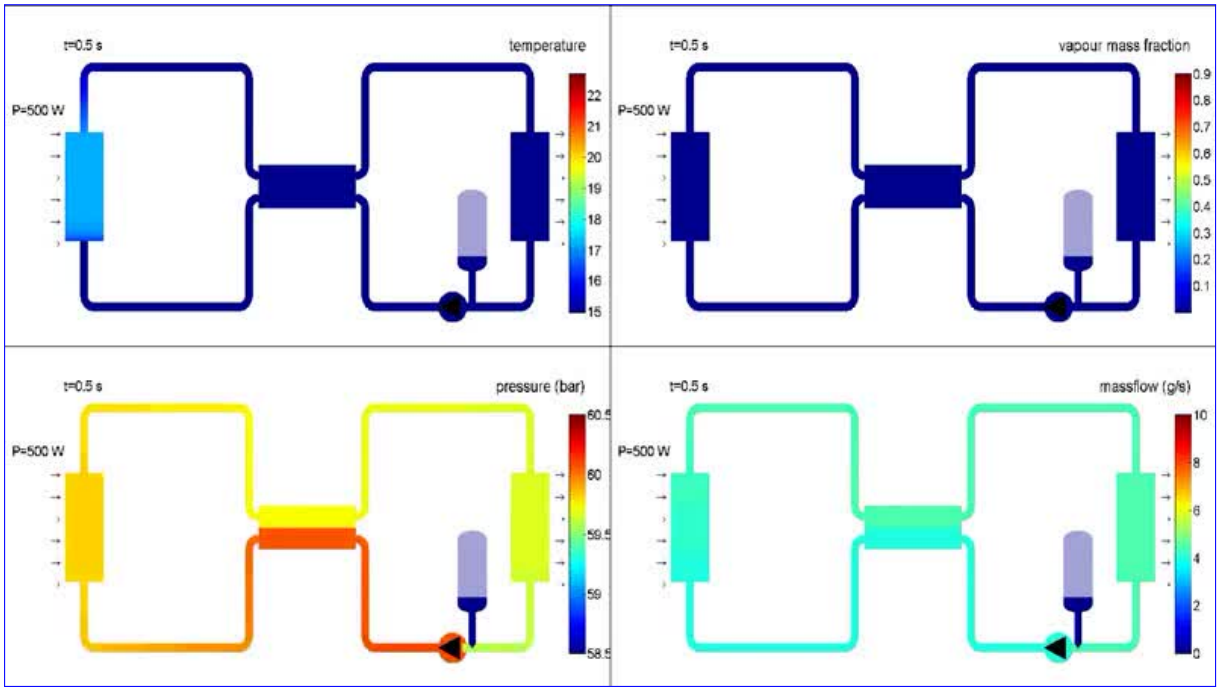

If clicking on the picture above does not run the movie then try opening the file 'movies/DynamicModelbasicCO2PCAv5.html' manually.

2Φ-MPFL in space

2Φ-MPFL system for AMS02:

- Alpha Magnetic Spectrometer (AMS02) is a large detector (7000kg!) for cosmic particles that was mounted on the International Space Station in May 2011. CO_2 is the thermal control fluid
- NLR is leading the international team for the thermal control system for the AMS02 tracker
- **So why has CO_2 been chosen as the cooling fluid?**

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Two-phase Mechanically Pumped Fluid Loop

- The tubing inside the tracker must have a small diameter
- However, the available pump only has a small pressure head
  → minimize pressure drop in the system by choosing an optimal fluid
- $$\Delta p \propto \overbrace{\left(\frac{\mu_l^{1/4}}{\rho_l h_{lv}^{7/4}} + \frac{\mu_v^{1/4}}{\rho_v h_{lv}^{7/4}} \right)}^{\text{fluid dependent}} \overbrace{\frac{L}{d^{19/4}}}^{\text{geometry dependent}} \underbrace{P^{7/4}}_{\text{heat input}}$$
- Figure of Merit based on low pressure drop is $M = 1/\Delta p_{\text{fluid dependent part}}$

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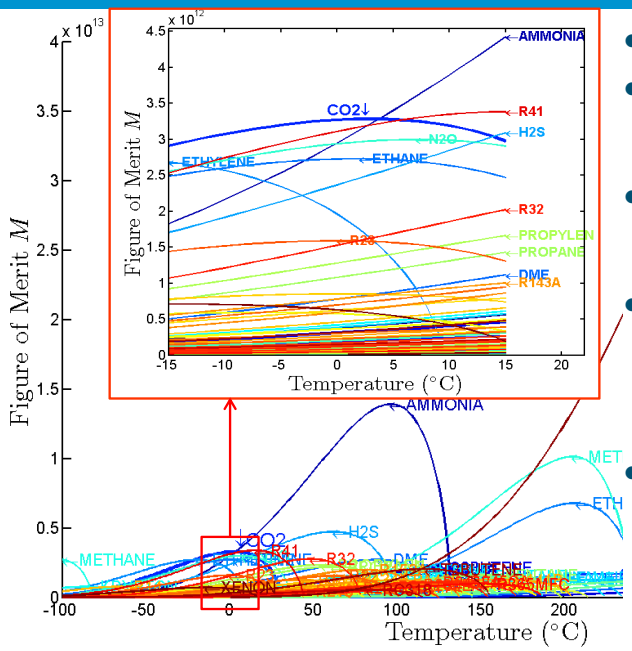
Two-phase Mechanically Pumped Fluid Loop



- CO_2 has the highest figure of Merit
- There are also other fluids with a similar *M*, such as ammonia, R41, N_2O, and ethane
- Some of these fluids would not have been found without the use of the figure of Merit
- After a detailed fluid trade-off, CO_2 was chosen because of low toxicity, inflammability, excellent radiation hardness and good material compatibility
- Other criteria for *M*, such as low pump power, are also possible

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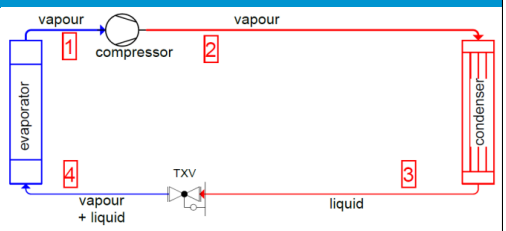
Heat pump



- A heat pump uses a compressor to raise the radiator temperature above the payload temperature
- This significantly increases the heat rejection capacity of the radiators
- Traditional compressors are too heavy and cause too much vibrations
- For this reason, a heat pump with a lightweight, low-vibration, high-speed (200,000 RPM) compressor has been developed in an ESA project
- The efficiency of a heat pump can be expressed with the Coefficient of Performance: $COP = P/w_{compressor}$
- So for a heat pump, the figure of Merit can be based on the COP → $M \propto COP$

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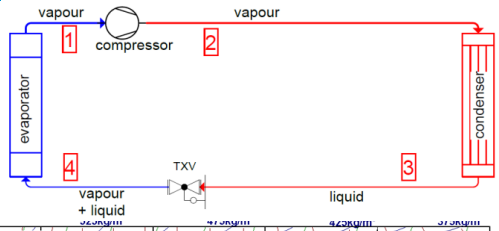
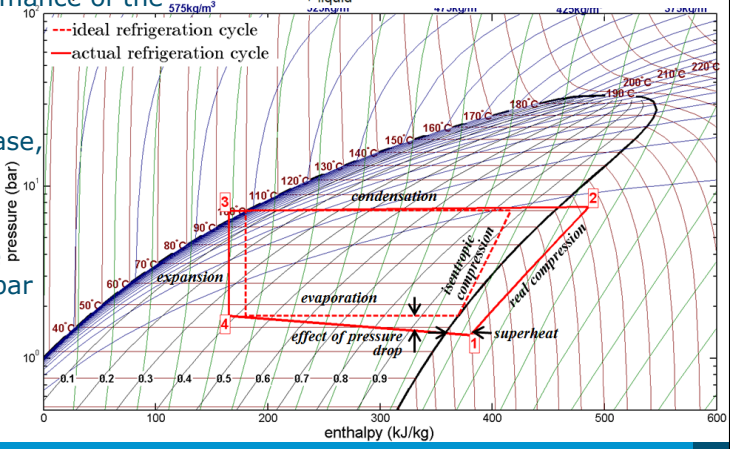
Heat pump

- The COP can be calculated from the enthalpies:
  $COP = P/W_{compressor} = \frac{h_1 - h_4}{h_2 - h_1}$
- The pressure drop in the system has a large influence on the performance of the system and must be taken into account
- The COP is calculated for all fluids in the REFPROP database, assuming $\Delta p = 0.4$ bar and 60% compressor efficiency
- For compressor reasons, the pressure must be below 14 bar





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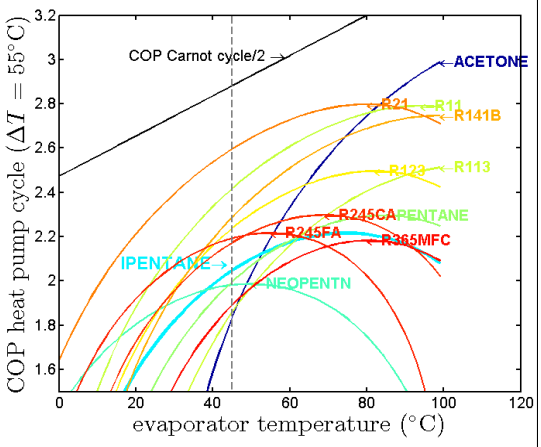
Heat pump

- The fluid selection tool shows that R21, R11, R141b, and R123 have the highest COP
- However, these fluids are banned or being phased-out according to the Montreal protocol
- The next best fluids are R245fa, R245ca, and isopentane (R601a)
- A detailed compressor analysis showed that the highest efficiency is obtained with isopentane, so this refrigerant is chosen for the heat pump application



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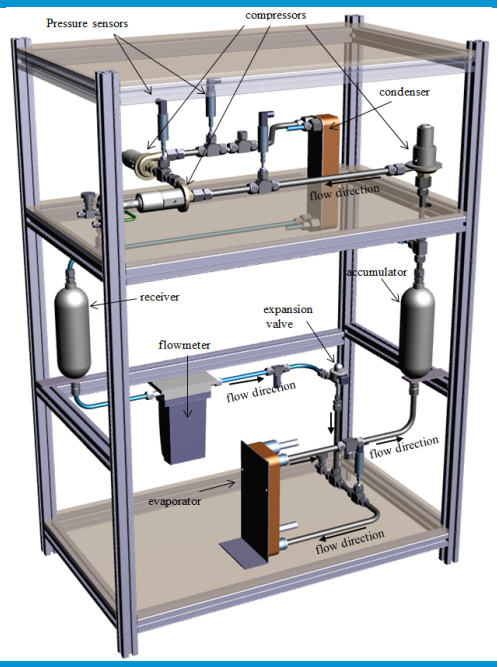
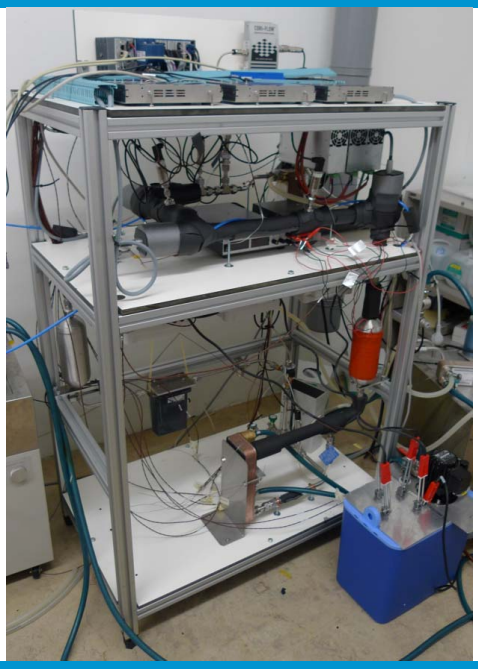
Heat pump measurements with isopentane





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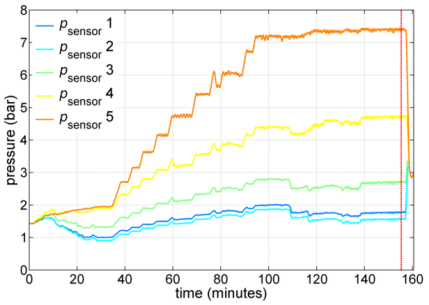
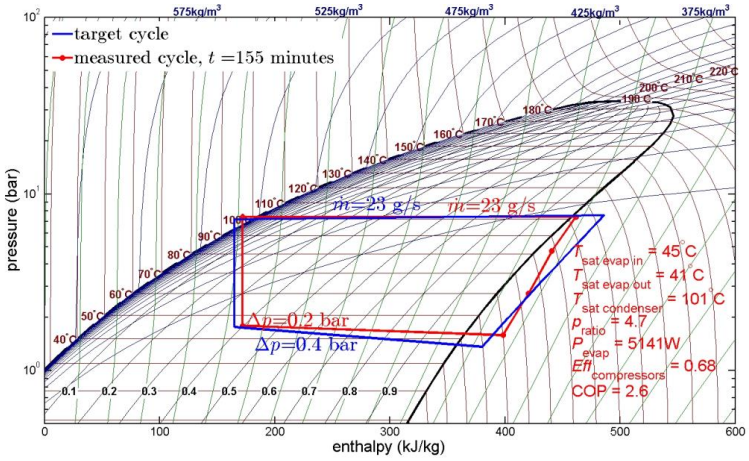
Heat pump measurements with isopentane

- Measurements have been carried out with isopentane as refrigerant
- The measured COP is 2.6, which is considerable higher than the ESA requirement of 2





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Conclusions

- With the figure of Merit, the most suitable fluids are selected from the REFPROP database for a wide range of applications
- With this systematic approach, fluids can be selected which otherwise would have been overlooked
- The use of the figure of Merit is implemented in a fluid selection tool
- With this fluid selection tool, the tedious process of finding and analyzing possibly suitable fluids can now be carried out with a single push on a button

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